

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

DRA/H2
NAGW-115

**Ice-Soil Mixtures:
Visual and Near-Infrared Remote Sensing Techniques**

(NASA-CR-174087) ICE-SOIL MIXTURES: VISUAL
AND NEAR-INFRARED REMOTE SENSING TECHNIQUES
Final Report (Hawaii Univ., Honolulu.) 21 p
HC A02/MF A01 CSCI 08L

N85-13358

Unclass
G3/43 01361

Roger N. Clark

Planetary Geosciences Division
Hawaii Institute of Geophysics
University of Hawaii
Honolulu, Hawaii 96822

Submitted to:
Fourth International Conference on Permafrost
February 1983

PGD Pub. No. 369



RECEIVED
A.I.A.A.
1983 APR 15 AM 10:54
T. I. S. LIBRARY

February 22, 1983

Abstract

The spectral properties of ice-soil mixtures are reviewed. Spectra of intimate mixtures of soil and ice are highly complex, non-linear functions of the optical properties of ice and soil. Water ice has an absorption coefficient which varies by several orders of magnitude in the visual and near infrared (0.4-3 μ m), and has several prominent overtone absorptions (at 2.0, 1.5, 1.25, and 1.04 μ m). Thus, different wavelengths can be used to probe to different depths in the surface as well as for different mineral impurity concentrations. Empirical and/or theoretical models might be used for deriving characteristic grain size of the ice or of the impurity minerals and for deriving abundance of the ice and rock or soil components. Quantitative analysis of remotely obtained reflectance spectra can only be performed using the absorption features in the spectra of ice and soil, and not by broadband response. This might be done by special selection of several narrow band filters in the near infrared which will adequately define the ice absorptions.

Introduction

Understanding the optical properties of water ice and mixtures of ice and soil are essential for remote sensing studies. The amount of sunlight reflected from a surface composed of ice and soil depends on the abundances and grain sizes of each mineral component as well as the absorption coefficients of the minerals, and the physical state of the ice-soil association. The spectral properties of an ice-soil intimate mixture (e.g. like frozen mud) are a highly complex (non-linear) combination of the end member spectral properties. Intimate mixtures are one end of the range of possibilities which may be encountered. The other end of the range is called an areal mixture, where the materials are optically isolated patches of the pure end members located on the surface. The spectrum of such a case is a simple linear addition of the spectra of the optically isolated patches of minerals weighted by the fractional areal coverage of each patch in the field of view of the detector. There is a continuous range of mixture possibilities in between the intimate and areal mixtures, as well as vertically stratified cases such as a frost layer on a soil. Inversion of a remotely obtained spectrum of a surface to determine mineral abundance is a formidable problem, if a quantitative and unique answer is desired. Fortunately, water ice has optical properties that are very different from those of other minerals which may allow reasonable abundances to be derived from remotely obtained spectra.

Ice

H₂O Ice contains absorptions in the infrared due to O-H stretches (3 μm), H-O-H bend (6 μm) and many translation and rotational modes at longer wavelengths. In the spectral region of reflected solar radiation, ~ 0.4 to ~ 2.5 μm , ice displays overtones of the above modes at 2.02, 1.52, 1.25, 1.04, 0.90, and 0.81 μm . In reflectance, scattering controls the light returned from the surface to the detector, and scattering can occur from ice-air interfaces (grain boundaries or crystal imperfections) or from impurities mixed in the surface such as a soil. Thus, even in a pure ice or snow, the effective grain size greatly controls the appearance of the reflectance spectrum (Figure 1). The words frost and snow are used interchangeably in this paper since there are no distinguishable spectral differences.

The mean path length that photons travel in a mineral is determined by scattering and by the absorption coefficient of the material. For instance, at 3.075 μm , the absorption coefficient of ice is 14008 cm^{-1} (Irvine and Pollack, 1968), and a path length of 1 micrometer results in absorption of 25% of the light, whereas at the center of the 1.04- μm ice absorption, the absorption coefficient is 0.34 cm^{-1} and a path length of 4.1 cm is required for the same 25% absorption. Thus, different wavelengths probe to different depths in an icy surface, and a large variation in optical path is an advantage for remote sensing studies since each absorption is sensitive to different amounts of impurities and to scattering due to different grain sizes.

Spectral Properties of Ice-Soil Mixtures

There has been considerable advancement in the understanding of the optical properties of ice and snow and the spectral properties of ice-soil mixtures over the last several years. Warren (1982) reviewed the optical properties of snow, concentrating on how the visual reflectance is affected by small amounts of impurities. Warren showed that parts per million of micrometer-size dust grains significantly change the albedo and color of the visual spectrum. Clark (1982) discussed the implications of using both visual and near infrared broadband detectors for remote sensing studies. The visual reflectance of a pure frozen water can vary from 1.0 for a fine grained frost to ~0.4 for an ice with little internal scattering which is characteristic of some terrestrial ice in the arctic and antarctic. With small fractions of a weight percent soot or dust, the visual reflectance can vary from unity to less than 0.1. The visual albedo of ice varies so much with scattering conditions due to grain size and small amounts of impurities, that it is unreliable to use the visual albedo alone for any quantitative remote sensing study.

Clark (1981a, b) studied the spectral properties of ice blocks, frosts of various grain sizes, and ice-mineral mixtures. Impurities in an ice or frost layer can radically change the appearance of the reflectance spectrum in the near infrared, as well as in the visual part of the spectrum. The addition of mineral grains dusted on the surface of a frost layer decreases the 1.5- and 2.0- μm absorptions roughly proportionally to the fractional areal coverage, but since the surface of the frost is not a flat layer but a "fairy castle" structure, the mineral grains are somewhat mixed in the uppermost part of the surface which results in a higher probability of a photon encountering an impurity grain. This results in reduced scattering and path length in ice,

and the albedo of the surface may be drastically reduced many times more than expected for a fractional areal coverage using an additive model for areal mixtures. Thus, mineral grains on a frost layer are detectable in very small quantities. For example, a fractional areal coverage <0.005 is detectable, if the mineral has suitable absorptions outside the major water ice features and the data are of sufficiently high quality, 0.5% precision, (Clark, 1981a).

In the case of a frost layer on a soil, a thick frost layer (>1 mm) is required to mask the soil at wavelengths shortward of $1.4 \mu\text{m}$ due to the low absorption coefficient of ice, but also depends on the mineral reflectance features and the frost grain size. Frost on a very dark surface (e.g. reflectance 6%) is easily seen even when only a small amount of frost is present (e.g. a few micrometer layer).

Spectral studies of minerals with adsorbed water show that the physically and chemically bound water absorptions, which occur at 1.4 , 1.9 and $2.2 \mu\text{m}$, do not shift appreciably in wavelength ($<.01\mu\text{m}$) over the temperature range from 273K to 150K , and are distinguishable from the broader water ice absorptions at 1.5 and $2.0 \mu\text{m}$ (Clark, 1981b).

In the case of intimate mixtures, a dark material intimately mixed with water ice can completely mask the water absorptions shortward of $2.5 \mu\text{m}$ (Clark, 1981a). The higher overtones ($0.8 \mu\text{m}$ to $1.25 \mu\text{m}$) are more readily masked than the stronger 1.5 - and 2.0 - μm absorptions; in fact, these weaker absorptions become suppressed with minerals dusted on frost. Even relatively high reflectivity (e.g. 0.8) grains, intimately mixed in a frost layer, can greatly reduce the scattering, thus limiting the path length and suppressing the higher overtone absorptions. These effects change the apparent higher to lower overtone absorption band depth ratios (e.g. the depth of the 1.25 - μm

band/1.5- μm band or 0.8- μm band/1.5- μm band) to a lower value. This is in contrast to a thin frost layer on an ice surface whose spectra show an increase in the corresponding apparent band depth ratios (Clark, 1981b).

More recently, Clark and Lucey (1983) have studied the spectral properties of mineral particulates intimately mixed in ice blocks in more detail, and one of their series of spectra are shown in Figure 2. Note how the ice bands at 2.0, 1.5, 1.25, 1.04, and 0.9 μm change with the particulate content. The relative depth of an absorption is defined with respect to a continuum (a smooth line such as a cubic spline polynomial) fit to the reflectance peaks between absorption bands (Clark, 1981b; Clark and Roush, 1983). If R_b is the reflectance at the absorption band center, and R_c is the reflectance of the fitted continuum at the same wavelength as R_b , then the band depth, D , is (Clark and Roush, 1983)

$$D = (R_c - R_b)/R_c. \quad (\text{eqn 1})$$

The band depths for the ice absorptions increase as the mean optical path length increases until significant absorption occurs in the wings of the absorption bands, then the bands become saturated and the depth decreases. A saturated band may almost completely disappear as seen with the 1.5- and 2.0- μm bands in the pure ice spectrum in Figure 2.

In order to help provide a calibration of ice purity from reflectance spectra, Clark and Lucey (1983) derived the curves of growth for several ice bands as a function of the photon mean optical path length in ice using the methods of Clark and Roush (1983). This is shown in Figure 3, and is similar to curves of growth produced from laboratory spectra in Figure 2. The albedo

of the particulate impurity greatly affects the spectrum and the curves of growth. The darker the particulate, the less scattering takes place in the surface, which results in a lower optical path length in ice and a smaller band depth. Clark and Lucey (1983) found that the band depth, D , divided by the continuum reflectance, R_c , removed the effects of particulate albedo as shown in Figure 4. Polynomials fit to such data for the 1.04-, 1.25-, 1.52-, and 2.02- μm bands provide calibration curves to abundance.

Remotely Sensed Spectra

From the previous discussion it was seen that some quantitative information can be obtained from remotely sensed spectra of an icy surface, given adequate spectral coverage and data precision. In remote sensing studies of the earth's surface, the atmosphere provides an additional difficulty, due to many absorptions, mainly from water vapor, oxygen and carbon dioxide (the latter two are relatively weak). Nevertheless, McCord and Clark (1979) have shown that the extinction due to atmospheric absorptions in this region can be removed in at least some cases. To do this, the same physical area must be measured for different path lengths through the atmosphere, at each wavelength. From a satellite or airplane this might be accomplished by changing the look direction while flying over the spot. However this adds another complication in that the viewing geometry with respect to the surface normal and the solar phase angle will also change. Thus, the scattering within the surface will also change and the spectral properties will change slightly. This is a second order effect, however, and will not significantly affect the crude abundance calculations outlined in the last section.

Recently, Hapke (1981) presented a theory for computing bidirectional reflectance of intimately mixed multimineralic surfaces from the complex indices of refraction, grain sizes, weight fractions, and densities of the mineral components. Most presentations of reflectance theories are in terms of deriving the absorption coefficient from laboratory spectra of a powdered sample, given the grain size of the material. However, Clark and Roush (1983) presented a method for deriving abundance from reflectance spectra. In a remote sensing study, if the materials present can be identified from absorption features in the reflectance spectrum, then the absorption coefficients of

the materials are known (or can be measured). The reflectance theories can be used to derive the average particle single scattering albedo from observations of the surface at many phase angles. Using the equations to compute the single scattering albedo, and if the absorption coefficient is unknown, the best that can be achieved is the determination of the product of grain size and absorption coefficient. If the absorption coefficients are known, however, then a non-linear least squares algorithm can be employed to solve for the grain size and the weight fraction of each component.

The ice absorptions may be adequately defined with as few as 9 wavelengths centered near 0.95, 1.04, 1.12, 1.25, 1.40, 1.52, 1.83, 2.02, and 2.24 μm . With these wavelengths, either the previously discussed theoretical or empirical methods might be used to derive abundance from a reflectance spectrum. If a detector system were to obtain images of a planetary surface at wavelengths such as those listed above, in principle it is possible to map the abundance of ice and other minerals.

In practice, for a terrestrial remote sensing project of this sort, an ideal data set would involve ~5 parameters: intensity at many wavelengths (~100 spectral channels from 0.5 to 2.5 μm), position (2 spatial), equivalent atmospheric thickness (air mass) and solar phase angle. The air mass data are required to correct for absorptions in the atmosphere, and solar phase angle data are required to determine the scattering properties (and thus microstructure) within the optical surface. Many spectral channels are required for mineral identification from observed absorption bands. Current technology is adequate for obtaining such a data set. A NASA project will acquire such a data set on a planetary scale beginning in 1989/90 with the Galileo mission to Jupiter where three satellites (ranging in size from Mercury to our moon),

whose surfaces contain abundant ice, will be mapped at 204 wavelengths and at a spatial resolution as high as 1 kilometer.

Conclusions

Reflectance spectra of ice-soil mixtures are very complex, non-linear functions of the optical and physical properties of the components comprising the surface. Fortunately, these spectra can be understood, and it appears that some quantitative information regarding mineral abundance can be derived.

Acknowledgements

The study was supported by NASA grant NAGW 115.

References

- Clark, R. N., 1981a, The spectral reflectance of water-mineral mixtures at low temperatures: Journal of Geophysical Research, v. 86, p. 3074-3086.
- Clark, R. N., 1981b, Water frost and ice: The near-infrared spectral reflectance 0.65-2.5 microns: Journal of Geophysical Research, v. 86, p. 3087-3096.
- Clark, R. N., 1982, Implications of using broadband photometry for compositional remote sensing of icy objects: Icarus, v. 49, p. 244-257.
- Clark, R. N., and P. G. Lucey, 1983, Spectral properties of ice-particulate mixtures: Implications for remote sensing I: Intimate mixtures: Journal of Geophysical Research, submitted.
- Clark, R. N., and T. Roush, 1983, Reflectance spectroscopy: Quantitative analysis techniques for remote sensing applications: Journal of Geophysical Research, submitted.
- Hapke, B., 1981, Bidirectional reflectance spectroscopy 1. Theory: Journal of Geophysical Research, v. 86, p. 3039-3054.
- Irvine, W. M., and J. B. Pollack, 1968, Infrared optical properties of water and ice spheres: Icarus, v. 8, p. 324-360.
- McCord, T. B., and R. N. Clark, 1979, Atmospheric extinction 0.65-2.50 microns

above Mauna Kea: Publication of the Astronomical Society of the Pacific,
v. 91, p. 571-576.

Warren, G. S., 1982, Optical properties of snow: Review of Geophysics and
Space Physics, v. 20, p. 67-89.

Figure Captions

Figure 1. The near-infrared spectral reflectance of A) a fine grained (~ 50 μm) water frost, B) medium grained (~ 200 μm) frost, c) coarse grained ($400\text{--}2000$ μm) frost and D) a ice block containing abundant microbubbles are shown. The larger the effective grain size, the greater the mean path that photons travel in the ice, and the deeper the absorptions become. Frost data from Clark (1981b). Ice data from Clark and Lucey (1983).

Figure 2. The reflectance spectra of ice blocks containing Mauna Kea soil of 15 micrometer mean grain size are shown (from Clark and Lucey). Note how the water ice band depths at 2.0, 1.5, 1.25, 1.04, and 0.90 μm change as a function of the weight fraction of the particulates in the ice. The particulate soil limits the photons from penetrating into the ice, thus a greater particulate weight fraction results in less photon path length in the ice and smaller absorption bands. The particulate reflectance also limits the photon path with darker grains reducing the multiple scattering and also the absorption band depths.

Figure 3. Theoretically derived curves of growth (from Clark and Lucey, 1983) for 5 ice absorptions are shown. The optical path is the photon mean path length in ice at the absorption band center. Since ice is less absorbing at wavelengths outside the absorption bands, the mean optical path lengths are as much as an order of magnitude greater than at the band centers.

Figure 4. The data from Figure 2 (crosses) plus reflectance data for ice-charcoal mixtures (solid boxes) and ice-kaolinite mixtures (open boxes) were used to derive the $1.04\text{-}\mu\text{m}$ ice absorption band depth divided by the continuum reflectance (from Clark and Lucey, 1983) as a function of the log weight fraction of particulates in the ice. Although there is a factor of about 20 between the reflectance of the bright kaolinite grains and the dark charcoal grains, division of the band depth by the continuum reflectance removes the effects of particulate contaminant reflectance. Thus the curve can be used for crude abundance determinations from remotely obtained reflectance data. Other ice absorption bands are sensitive to different amounts of impurities. Some scatter in the charcoal data is due to near zero band depths and very low continuum reflectance, thus approaching zero divided by zero.

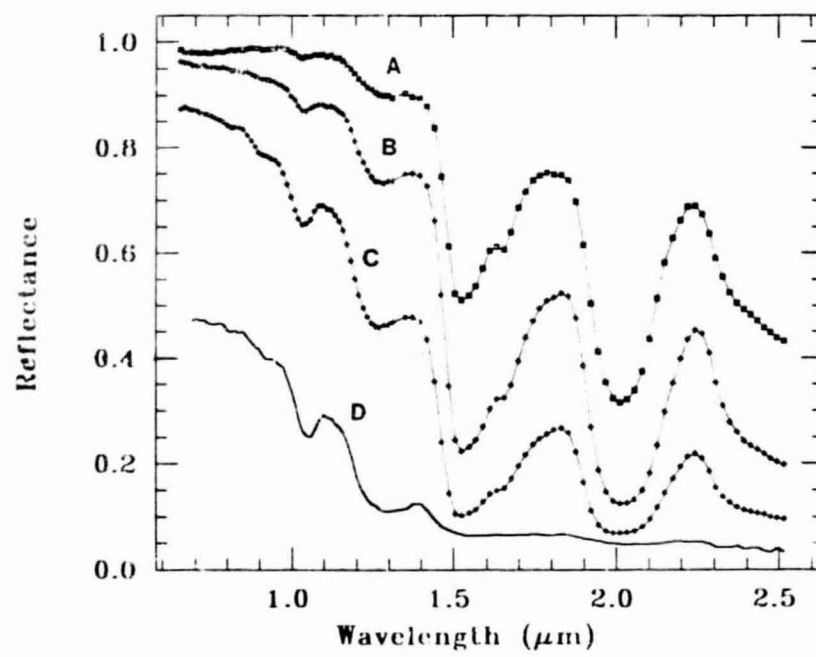


FIGURE 1

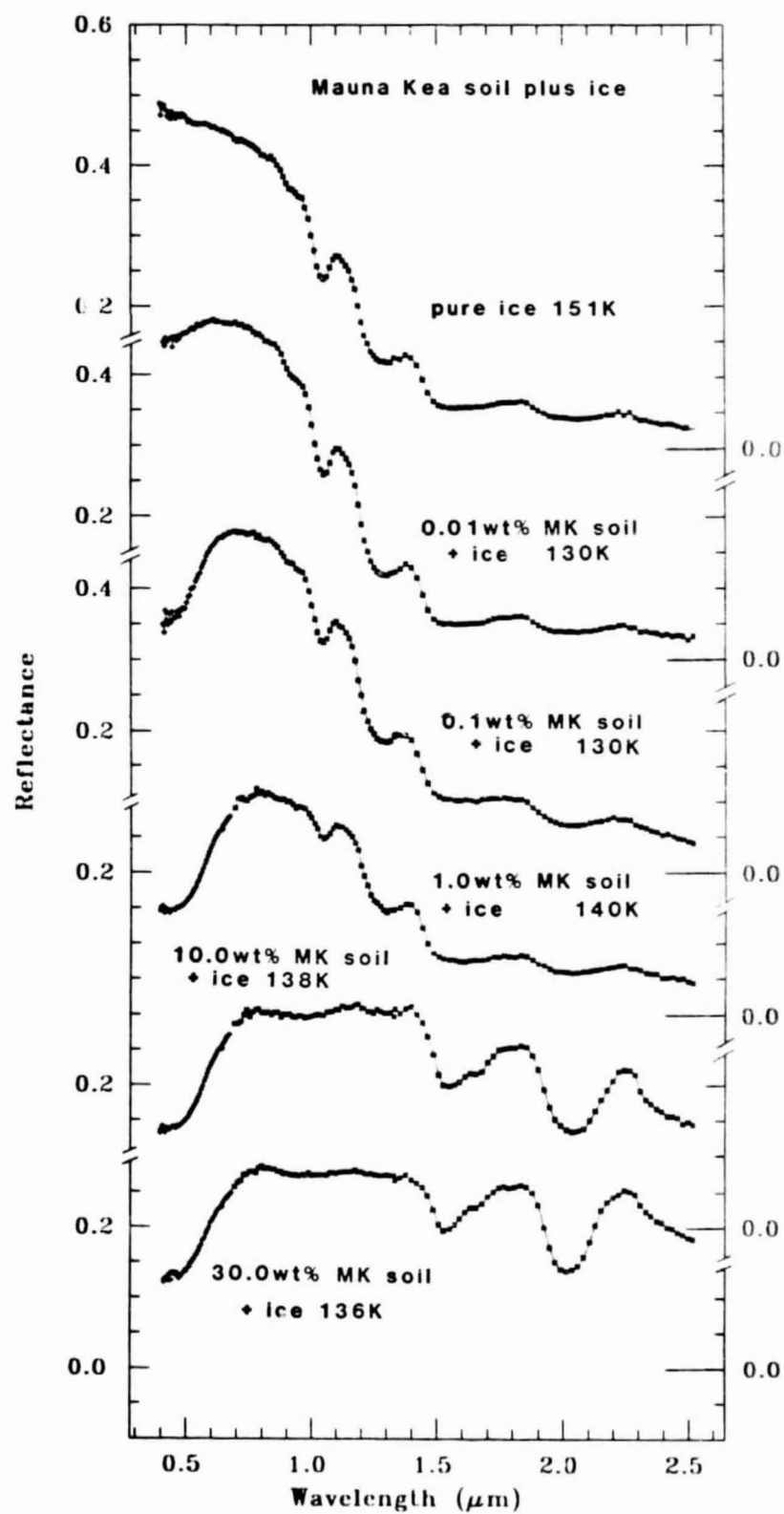


FIGURE 2

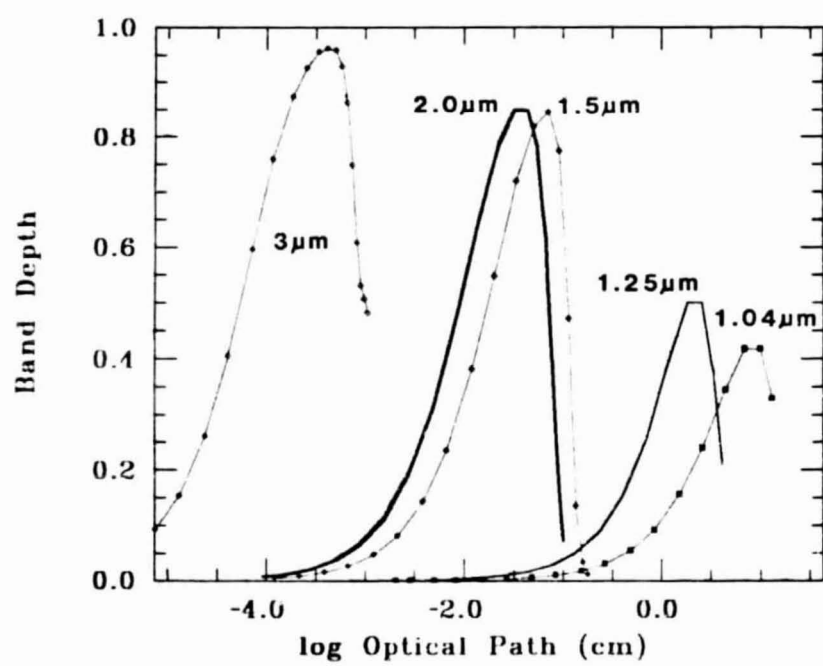


FIGURE 3

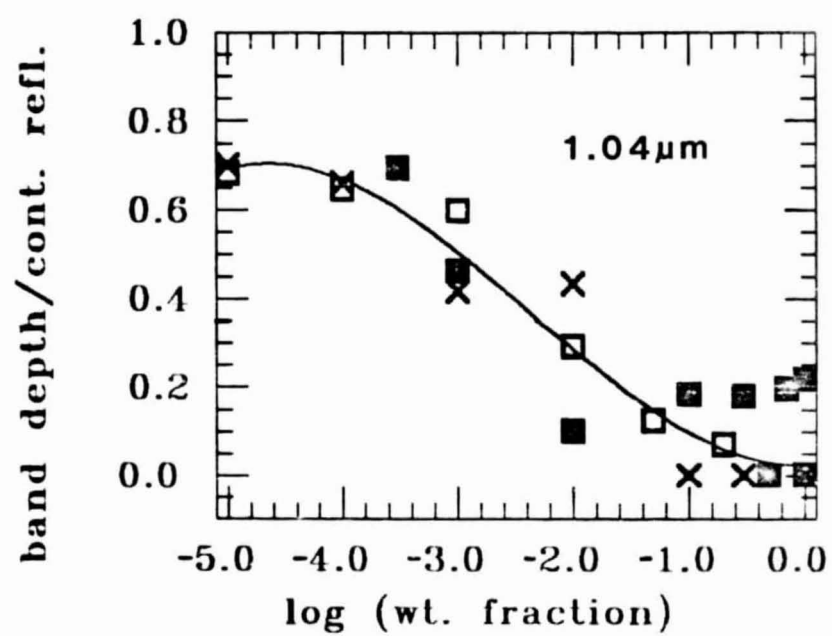


FIGURE 4